A Computational Method for Optimizing Fuel Treatment Locations

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***Abstract**—Modeling and experiments have suggested that spatial fuel treatment patterns can influence the movement of large fires. On simple theoretical landscapes consisting of two fuel types (treated and untreated) optimal patterns can be analytically derived that disrupt fire growth efficiently (i.e. with less area treated than random patterns). Although conceptually simple, the application of these theories to actual landscapes is made difficult by heterogeneity (fuels, weather, and topography) compared to the assumptions required for analytical solutions. Here I describe a computational method for heterogeneous landscapes that identifies efficient fuel treatment units and patterns for a selected fire weather scenario. The method requires input of two sets of spatial input data: 1) the current fuel conditions and 2) the potential fuel conditions after a treatment (if it were possible). The contrast in fire spread rate between the two landscapes under the weather scenario conditions indicates where treatments are effective at delaying the growth of fires. Fire growth from the upwind edge of the landscape is then computed using a minimum travel time algorithm. This identifies major fire travel routes (areas needing treatment) and their intersections with the areas where treatments occurred and reduced the spread rate (opportunity for treatment). These zones of treatment "need and opportunity" are iteratively delineated by contiguous patches of raster cells up to a user-supplied constraint on percentage of land area to be treated. This algorithm is demonstrated for simple and for complex landscapes.*

Introduction

Fuel treatment effects on wildland fire behavior have long been documented at the stand level (Biswell et al. 1973, Wagle and Eakle 1979, Helms 1979, Pollet and Omi 2002, Fernandes and Botelho 2003, Graham 2003). Prescribed burns and thinning operations change fuel structure and have together been successful in modifying fire behavior and consequent effects in the areas treated (Weaver 1943, Kallender et al. 1955, Cooper 1961, Martin et al. 1989, Graham et al. 1999, Schoennagle et al. 2004, Graham et al. 2004, Agee and Skinner 2005, Cram et al. 2006). The landscape level, however, is composed of many stands and mixtures of fuel conditions through which large fires burn, and there has been little work on strategies for treatment at this broad scale. Prescribed burning and general fuel management will be a necessary part of mitigating and even reversing effects of fire suppression (Arno et al. 1991). Evidence shows that even widespread treatments that change fire behavior at the stand-level can be circumvented by larger fires (Salazar et al. 1987, Dunn 1989, Finney et al. 2005). This paper reports on an algorithm that optimizes the placement of treatment units to limit this circumvention and thereby interrupt the movement of large fires.

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Precedence for landscape-level fuel modifications is found in the patchwork or mosaic formed by free burning fires in large wilderness areas in the western United States. Here, patterns of old burns delay and detour later fires (van Wagtendonk 1995, Parsons and van Wagtendonk, Rollins et al. 2001). These interactive effects are possible when fire frequency is high enough to maintain some unknown fraction of the landscape in a modified condition. By comparison, intensive fuel treatment methods are expensive and wholesale treatment of large landscapes is impossible for practical reasons including land ownership, conflicting management objectives, and funding. Typically, the amount of land area and the locations of treatments are constraining, thus, the question of where to place treatments becomes a problem suitable for optimization.

Theoretical work for artificial landscapes has shown optimum efficiency from a pattern of rectangular treatment units that reduces fire growth rates with a minimum of area treated (Finney 2001a). Rectangular units that partially overlap in the predominant fire spread direction (determined from historic climatology) allow the fire to move through and around them at the same rate. Fire growth is slowed by the pattern because fire progress is dominated by lateral movement. When small fractions of land are treated, these patterns are efficient compared to random arrangements (Finney 2003, Loehle 2005). Random patterns may require several times as much treatment to reduce fire growth rates to comparable levels (Gill and Bradstock 1998, Bevers et al. 2004). Although conceptually simple, the application of these theories to actual landscapes is only just beginning (Hirsch et al. 2001) and is made difficult by the heterogeneity of real landscapes (fuels, weather, and topography) compared to the assumptions required for analytical solutions (Finney 2001b).

The computational method reported here uses spatial GIS data to represent the heterogeneity of actual landscapes and produces a map of treatment areas that collectively disrupt fire growth at scales coarser than the individual treatment units. The algorithm is applied to simple and complex landscape conditions showing that the treatment pattern is one of many that achieve effective results comparable to those suggested by the analytical theory.

Assumptions And Methods

Fire Sizes and Severity

The objective explicitly assumed by this analysis for landscape fuel management is to delay the growth of large or "problem" fires. Information on such fires is readily obtained for most wildland areas from local or regional fire history or fire atlases (Figure 1). The reasoning for this assumption follows from the conditions that foster the growth of such fires in areas dominated by suppression-oriented management in western North America. Here, fires become large by escaping initial attack and then spreading far from where they start. Large fires are resistant to suppression efforts because of the dry and windy weather that contributes to their rapid growth, the sheer size and length of perimeter they present to control, and the fire behaviors produced under the extreme weather conditions originating their escape (crown fire, spotting). Suppression success typically occurs only when durable changes in the weather abate rapid fire growth. During periods of active spread, such fires are responsible for the greatest damages to watersheds, ecosystems, and

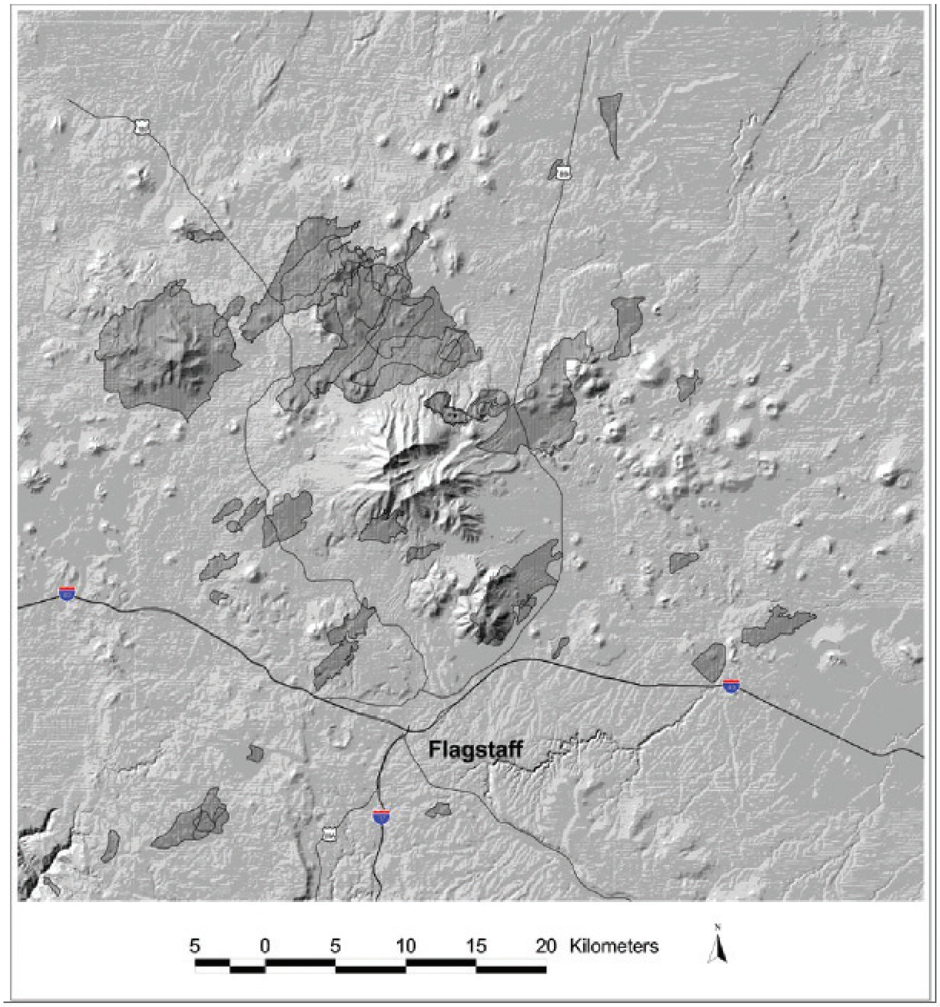

Figure 1—Fire history atlas around Flagstaff, Arizona shows large fires are mostly oriented along a southwest-northeast axis. Wind conditions associated with these fires are about 35 mph (56 kph) with fuel moistures from 3 to 5 percent.

present the greatest threats to human developments beyond the borders of the wildlands *per se*. Managing the condition of the landscape and the spatial fuel structure, therefore, offers the only possible means to resist the growth of fires under such conditions, reducing the spread rate and ultimate size of the fires (Gill and Bradstock 1998, Brackebusch 1973). This contrasts with the use of fuel breaks (Green 1977, Weatherspoon and Skinner 1995, Agee et al. 2000) which require active fire suppression for benefits to be realized. Fuel is the only element of fire behavior that is manageable, since weather and topography are beyond human control.

Weather Conditions

By targeting large fires for treatment efforts, the analysis of fire behavior can be restricted to a small subset of weather conditions contributing to the growth of those kinds of fires. Large fires typically occur under the most extreme weather conditions that originate their escape from initial attack. The weather during historic large fires is well known to local fire management officials and can be synthesized from climatological records (Rothermel 1998, Mutch 1998). These weather conditions provide critical data on general fire spread directions and spread rates for all fuel types on the landscape and narrows the focus of fuel management efforts to specific ranges of humidity, fuel moisture, and winds (Figure 1). By assuming a single set of specific weather conditions for large fires (fuel moistures across a landscape, wind speed and direction) fire behavior can be calculated for all areas of each landscape.

Sizes of Fires Greater than Fuel Treatment Units

The large size of these fires relative to the size of treatment units also suggests that the starting locations of fires can be ignored. This assumption allows the analysis to focus on the directions of fire movement. Large fires moving across landscapes encounter smaller treatment units with relatively wide fronts that have become largely independent of the exact ignition location. The major direction of fire movement is, however, critical because the rapid spread rates of the heading fire (moving with wind and slope) burn the most acreage with the highest intensities (Catchpole et al. 1982). Heading fire is more important to modify than flanking and backing portions of the fire which have lower intensities and cause less severe fire impacts.

Fuel Treatments

The fuel treatment optimization procedure described below depends on fire behavior contrasts between the two fuel profiles burning under the target weather conditions: one represents the starting conditions or current state of fuels and forest structure, and the second represents the fuel conditions following treatment (Figure 2). The assumption here is that desired fuel conditions can be identified on a stand-by-stand basis across the landscape for all stands where treatment is possible. These fuel conditions are represented across a large landscape as a rectangular grid at a fixed resolution. The cells of the grid are assumed uniform at scales finer than the resolution in terms of fuels, topography, and weather. The treated landscape describes the potential areas for treatment that must total more than the constraint imposed on total area treatable within the planning horizon. Treatment prescriptions within each stand or cell on a landscape, such as prescribed burning or various stand-level thinning guidelines can vary to reflect local objectives or restrictions on activities. Although any prescription can be applied, field evidence consistently suggests that fuel treatment prescriptions achieve reductions in wildfire spread rate and intensity by removing surface fuels through prescribed burning and decreasing the continuity between surface and canopy fuel strata through “low-thinning” (van Wagtendonk 1996, Pollet and Omi 2002, Agee and Skinner 2005). Mechanical treatments that leave slash or don’t remove pre-existing surface fuels may not change fire behavior sufficiently (Graham 2003, Raymond and Peterson 2005, Cram et al. 2006) or even exacerbate fuel hazards (Alexander and Yancik 1977). Lands excluded from treatment consideration retain the identical fuel descriptions in both landscapes or involve prescriptions that increase the fire spread rate. Thus, the optimization will choose from the lands where treatments change fire behavior to achieve the greatest collective reduction in landscape fire spread rate.

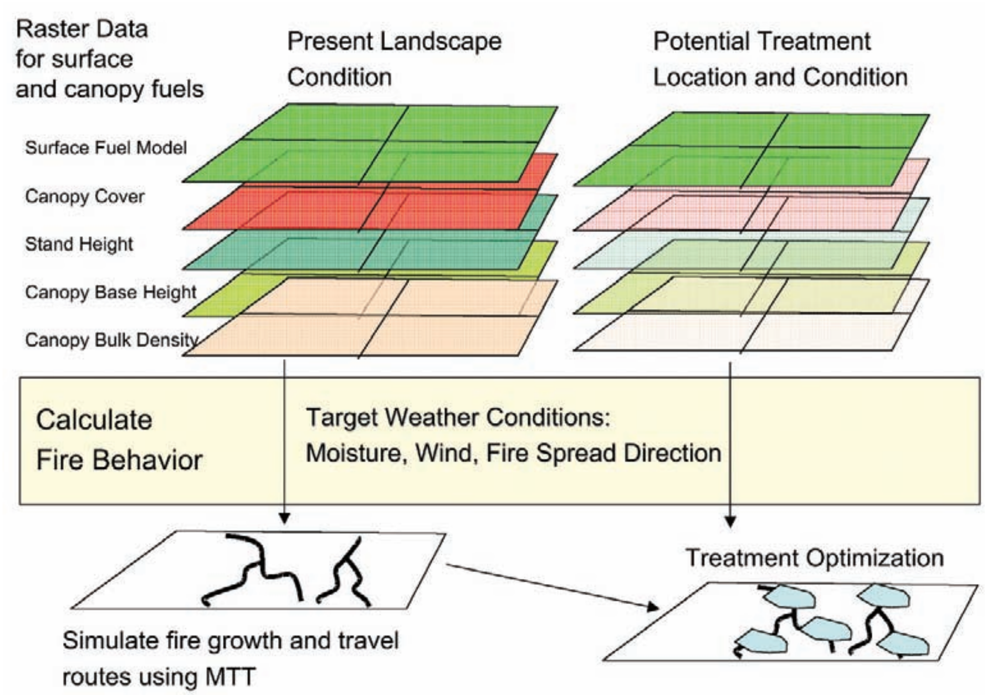

Figure 2—Two landscape fuel conditions area required for the optimization algorithm. The first landscape represents the pre-treatment or current fuel conditions whereas the second landscape represents the potential treatment conditions (i.e. modifications of fuel strata) everywhere treatments can potentially be located. Both landscapes are processed for fire behavior under the "target" weather conditions (i.e. those weather conditions that the treatments are designed for).

Algorithm

The objective of the fuel treatment optimization is to find the specific treatment areas that reduce fire growth for the target weather conditions by the greatest amount. In other words, it is attempting to maximize the minimum travel time for fire moving across the landscape. With the emphasis on fire travel time, a critical component of this optimization is a method for calculating fire growth under the target weather conditions. Fire growth simulation using a minimum-travel-time algorithm (Finney 2002b) is well suited to this task because it rapidly produces a fire arrival time field for a given ignition (which can be contoured to visualize fire growth at constant time intervals) and records the travel routes of fire movement from one node to the next (Figure 3). Both fire growth contours and travel routes are used by the fuel treatment optimization.

The optimization algorithm begins by dividing the landscape into a series of parallel strips oriented perpendicular to the main fire spread direction (Figure 3). The width of these strips is determined as a user input that

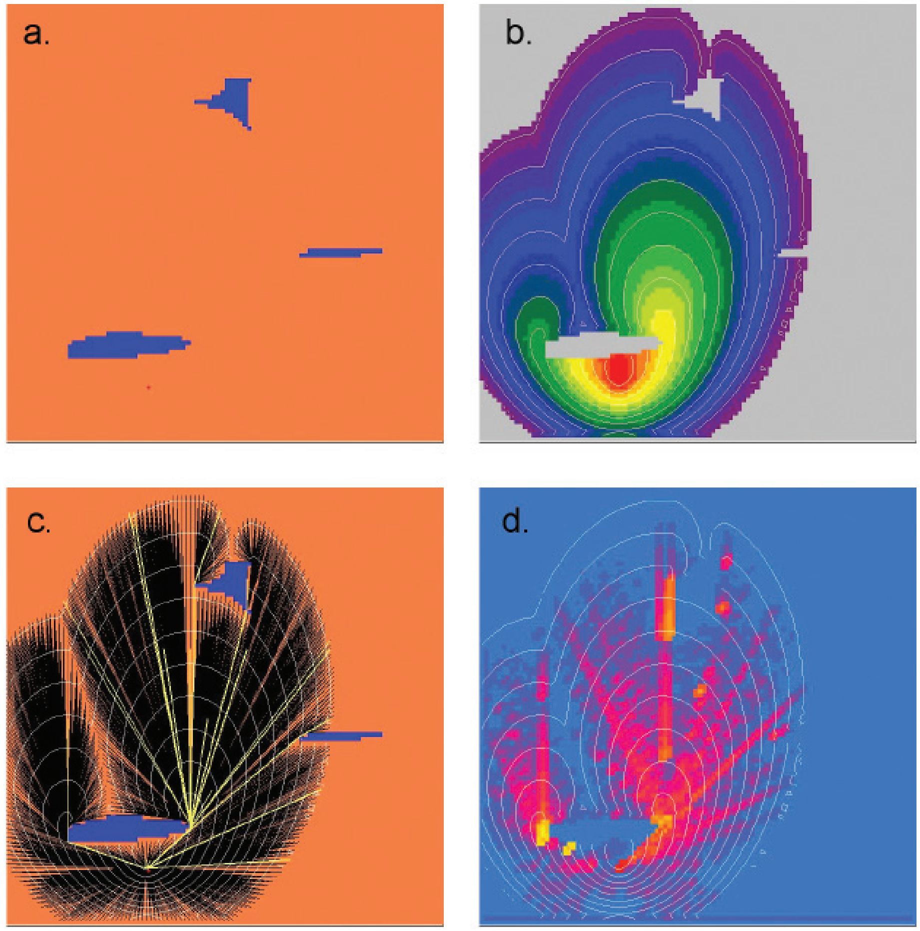

Figure 3—The fire behavior simulation uses a minimum travel-time (MTT) algorithm that (a) for a given landscape (b) produces an arrival time map which can be contoured to indicate fire progression and (c) displayed along with fire travel routes which correspond to calculations of "fire influence" (i.e. the area burned as a result of burning through that grid cell). All travel paths are shown in (c) as fine black lines and the "major" travel paths chosen at specified distance intervals and are indicated by bold yellow lines.

regulates the maximum dimension of treatment units allowed. This is similar to the method described by Finney 2002b, but this algorithm produces a deterministic solution:

1. Beginning with the upwind strip, fire growth and minimum travel routes are computed (Figure 4a). Concave segments along the fire arrival time contour are identified. These segments are concave in terms of the fire arrival time at a particular row of the landscape, which means that they start and end with a local maximum arrival time (Figure 4b).
2. Within the strip, the minimum travel time path for each segment is identified and followed backwards in time and space to record intersections with areas where fire behavior differences exist between the two landscapes (Figure 4c).
3. A choice is made for the best place to start the fuel treatments for each segment. The choice was based on criteria of having the earliest time where fuel treatments are possible. Arrival times are reset to infinity for all nodes (on the entire landscape) having an arrival time later than the time at the starting location.

4. The minimum travel-time algorithm is re-run for the strip using the post-treatment landscape data (Figure 4d). This is done for the entire strip separately for each segment identified in #1 above since the time contour used as starting point for fuel treatments identified in step 3 is typically different for each segment. The new arrival time map is stored for each segment and represents the rate of fire growth assuming all fuel treatments have occurred.
5. An iterative procedure identifies and delineates treatment units within the strip that have sizes and shape for efficiently retarding fire growth. A treatment unit is identified as a contiguous group of cells marked as treated using a contagion algorithm (Figure 4e). For each travel path the process marks treatable contiguous cells with arrival times greater than the starting point up to a time limit that is iteratively increased until the specified fraction of the landscape (strip) is treated. For each treatment unit, the contiguous block of marked cells is expanded laterally until the forward time difference is also reached. This creates a treatment unit that approximates the balance between time required for spreading through the unit and spreading around the unit (Finney 2001a).

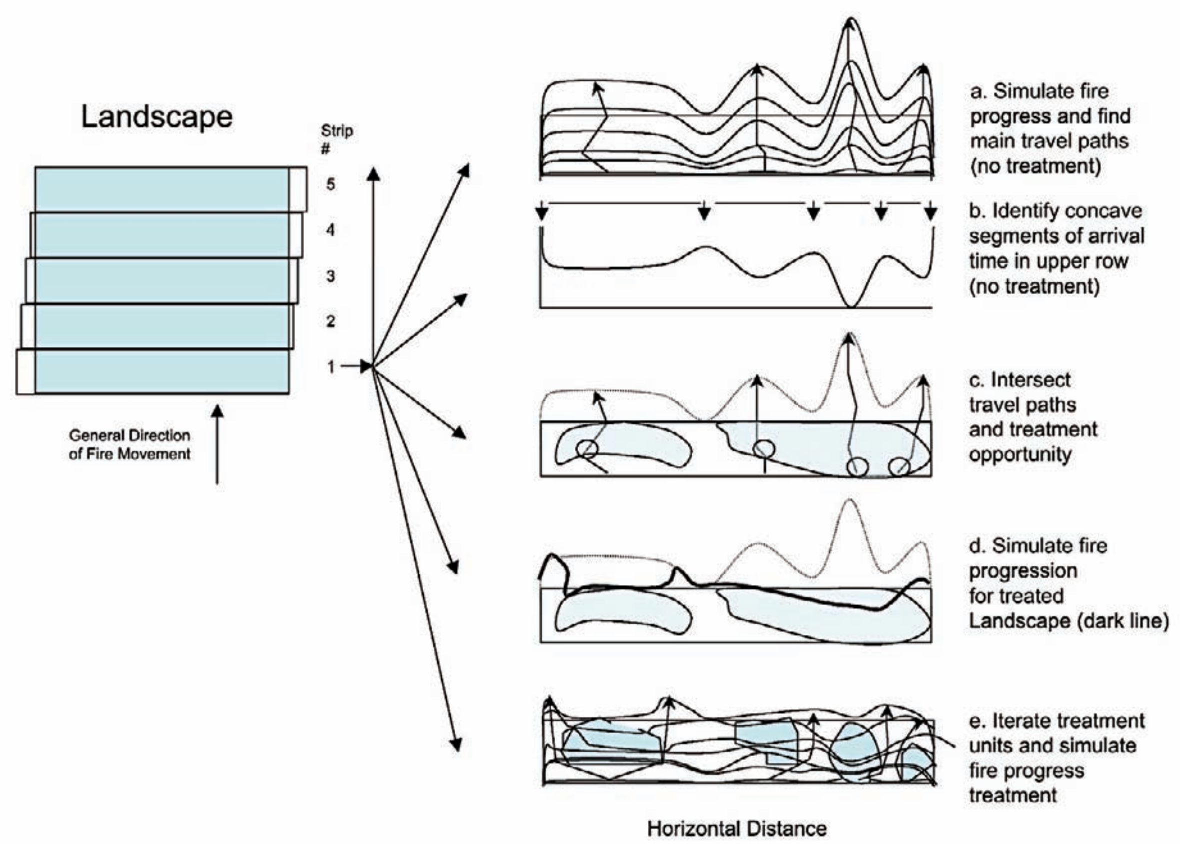

Figure 4—Optimization process begins by dividing the landscape into rows. For each row beginning with the row farthest upwind (a) fire growth for the pre-treatment landscape is calculated using the MTT calculation to identify travel routes and produce an arrival time map (b) the concave segments of arrival time are identified at the ending row, (c) intersections of the major fire travel paths and the treatment opportunity are identified (areas where treatments reduce the fires spread rate) and the point with the earliest arrival time of this intersection is recorded, (d) fire growth for the potential landscape is calculated from the starting time identified in (c), and (e) iteration of treatment unit size and shape is performed.

The algorithm assumes that the fire front will have a rippled time contour or "fingers" at the forward edge produced by varying spread rates that result from fuels, topography, or wind patterns. The algorithm targets fuel treatments to block these fingers since they are local zones of faster spread. For relatively uniform conditions, where little or no variation exists, the algorithm must be modified to place fuel treatments by some other rule. The rule used here within a given strip was a systematic and regular spacing, which produces the ripples at later time periods.

In optimal regular patterns (Finney 2001a) the most efficient treatment unit size depends on overlap and separation of neighboring treatment units. These dimensions are constant among units, and as such, are difficult to transfer directly to actual landscapes that contain complex variation in fuels, topography, and perhaps weather (wind direction, fuel moisture). The regular patterns don't apply here because the size and orientation of a given treatment unit is only efficient in the context of other possible units encountered immediately before and after by fire moving across the landscape. Yet, each unit modifies the path of fire into succeeding units. Thus, a compromise was undertaken for the algorithm that assumes that the delay of fire spread through the unit must be twice the delay in circumventing it. This will not be strictly valid if the fuel conditions downwind of the treatment unit are substantially different from those upwind.

Evaluation of the Algorithm

Two kinds of landscapes were used to evaluate the performance of the algorithm. First, an artificial simple landscape with several slow-burning fuel patches was used to test the ability of the algorithm to produce treatment patterns similar to the theoretical patterns described by Finney (2001) and illustrate the sensitivity to localized non-uniformities in the landscape. Here fuel treatments were implemented to reduce spread rate to $1/20^{th}$ of the untreated rate. The second landscape was located near Flagstaff Arizona. The historic fires were plotted and the predominant SW to NE orientation of the large wildfires was used to orient the treatment units against this major spread direction. Weather for the fire simulations were chosen at 99^{th} percentile of the historic National Fire Danger Rating System (NFDRS) index Energy Release Component for fuel model "g" (ERC(g)) which provides the fuel moisture content of the fuel components required for fire behavior modeling. Wind speed and wind directions were chosen to reflect the period of major fire growth associated with the historic large fires (Figure 1) that have burned in this area. Treatment prescriptions were only applied to ponderosa pine and mixed conifer forest areas in public ownership and consisted of changing surface fuels to fuel model 9 (Anderson 1982) increasing the crown base height and decreasing crown bulk density (both making crown fire more difficult). No treatment was permitted in meadows, on privately owned lands, or in a designated USFS Wilderness area in the north part of the area.

The response of the fire behavior to the various treatment options was measured in terms of average spread rate, relative change in wildfire size, and conditional burn probability. The conditional burn probability was determined by random fires simulated under the target weather conditions (Finney 2002a) for varying amounts of time (resulting in various fire sizes after 360, 720, and 1080 minutes of spread). This probability is "conditional" because is represents the probability of burning once a fire becomes large (>100 ha) or escapes initial attack, which typically occurs at a rate of less than 2% per year (NIFC 2002, Neuenschwander et al. 2000). Mean spread rate was obtained by dividing the average arrival time for the last row in the landscape by the linear travel distance.

Results

Treatment optimization for the simple landscape produced partially overlapping patterns similar to those of the analytical model (Finney 2001a) with the exception of the downwind edge of the few slow-burning patches (Figure 5). Patterns were similar when the optimization was directed to vary the sizes of treatment units. The average spread rate of the fire across the entire landscape showed the same response to increasing amounts of treatment as average fire sizes and average burn probability (Figure 6) for a given size of simulated fire. Burn probabilities were higher when larger fires were simulated but responded the same across the range of treatment percentages (Figure 6b,c). In addition, the increased efficiency of the optimal pattern compared to random treatment patterns was similar to the same comparisons for theoretical patterns (e.g. Finney 2003).

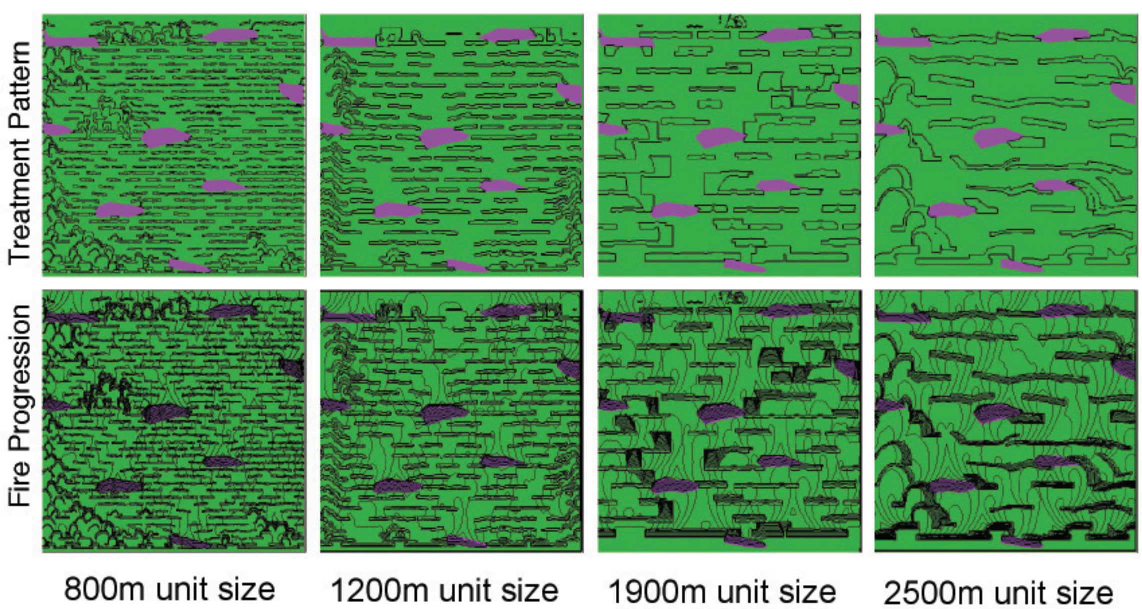

Figure 5—Treatment optimization runs for a simple flat landscape that contains eight small patches of slow-burning fuel (purple). From left to right the maximum treatment dimension is increased from 800 m to 2,500 m. Treatment units are shown independently along with the fire progression which reveals that treatment units cause repeated disruptions of fire movements.

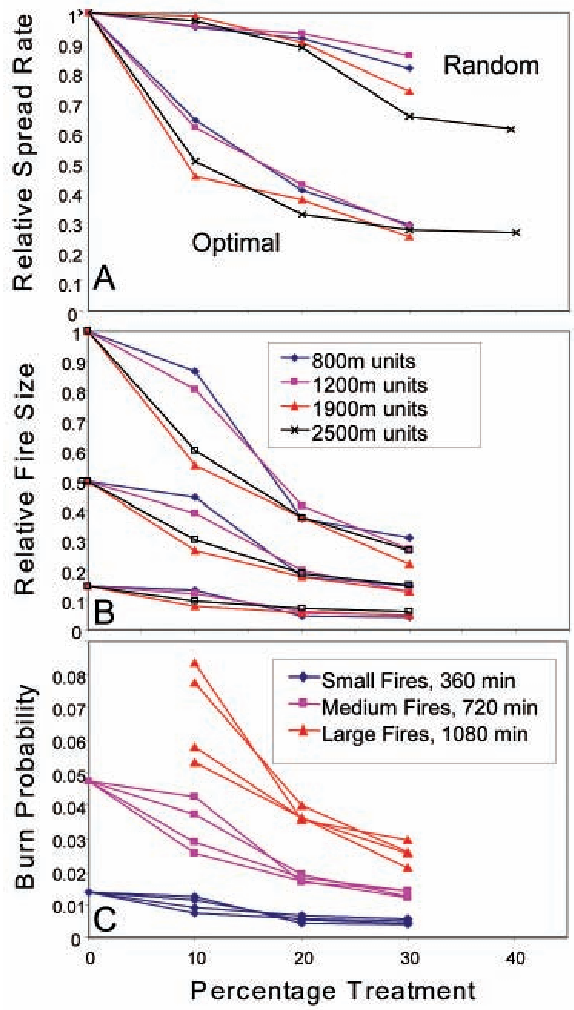

Figure 6—Summary of optimization results for simple landscapes over ranges of treatment amount were measured in terms of (a) average spread rate across the landscape, (b) average fire sizes for 1,000 simulated randomly ignited fires of different durations, and (c) average burn probability for the landscape determined from 1,000 random ignitions.

The optimal patterns for the Flagstaff landscape were less systematic than the patterns on the real landscape (Figure 7) and were strongly influenced by areas where treatment was precluded by ownership (private and designated wilderness) or vegetation type (i.e. meadows represented by grass fuels (Fuel Model 1)). The optimal pattern was more efficient at all levels of treatment than the random pattern (Figure 8a). However, the presence of untreatable area interspersed among the forests provided conduits for rapid fire spread and decreased the efficiency of the optimal pattern in retarding overall fire growth compared to random patterns as seen in the simple landscape and theoretical comparisons (Figure 8a). As with the simple landscapes, the relative fire sizes and conditional burn probability decreased with amount of treatment (Figure 8b,c).

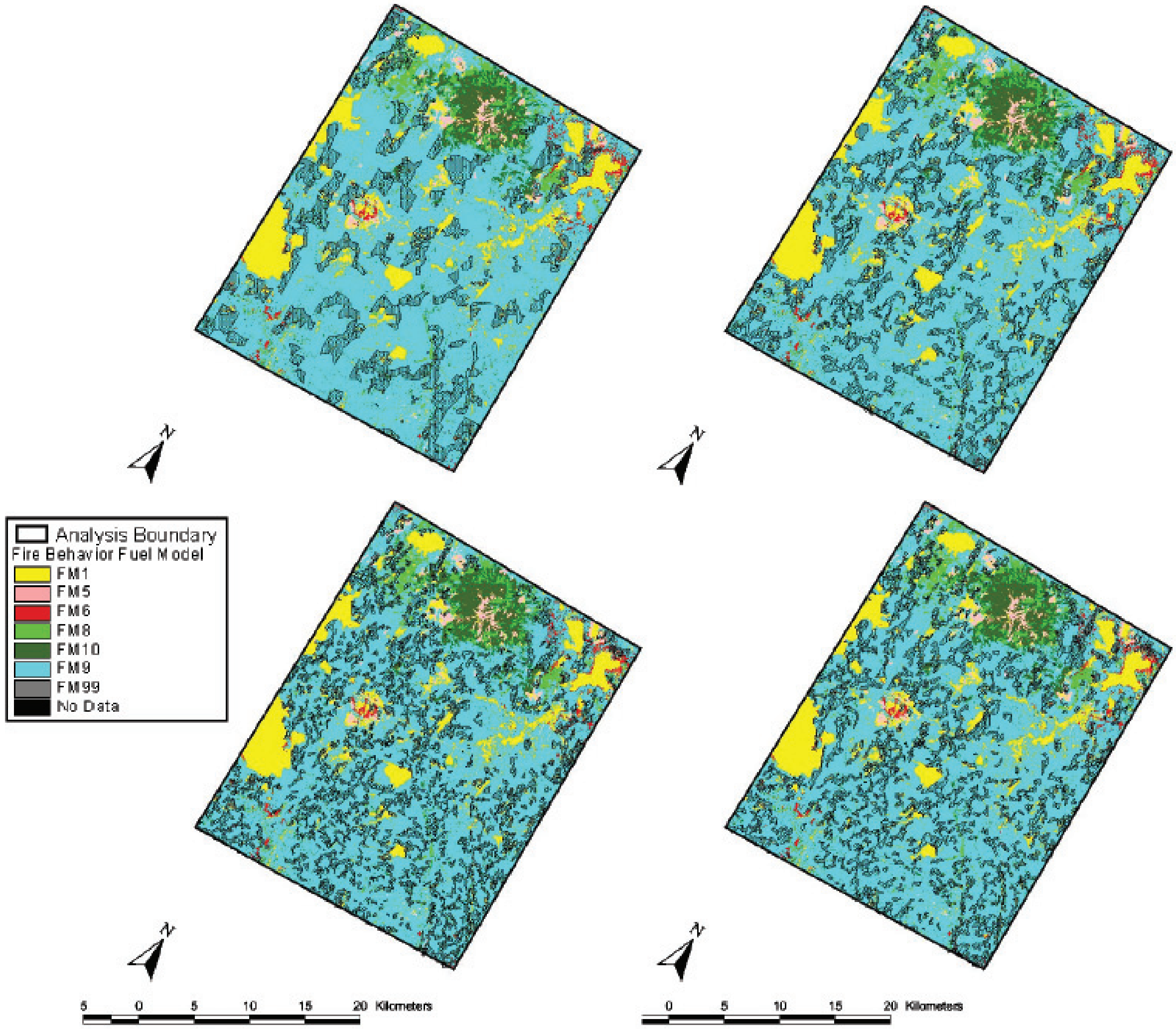

Figure 7—Optimal treatment patterns for the Forest Ecosystem Restoration Analysis project (FERA) for an area surrounding Flagstaff, Arizona. Each pattern represents 20% of the analysis area in treatments with only the treatment size varying by alternative. 2,500 m (a), 1,200 m (b), 800 m (c), and 600 m (d). The analysis area is 2,906 km^2 and 168,853 ha within the Kaibab and Coconino National Forests and is a portion of a larger landscapes (809,375 ha).

Discussion

This study showed that an optimization algorithm produced treatment patterns on simple landscapes with impacts on spread rate similar to the analytical solutions for similar landscapes (Finney 2001a). This is encouraging because performance on complex landscapes cannot be directly assessed relative to theoretical results. Relative performance of optimal patterns on both simple and complex landscapes could be assessed in relation to random patterns. This comparison suggested that optimization efficiently reduced spread in both landscapes but that the presence of untreatable areas within the landscape compromises the efficiency of the overall pattern. The poor efficiency of the random patterns is also similar to theoretical results (Finney 2003).

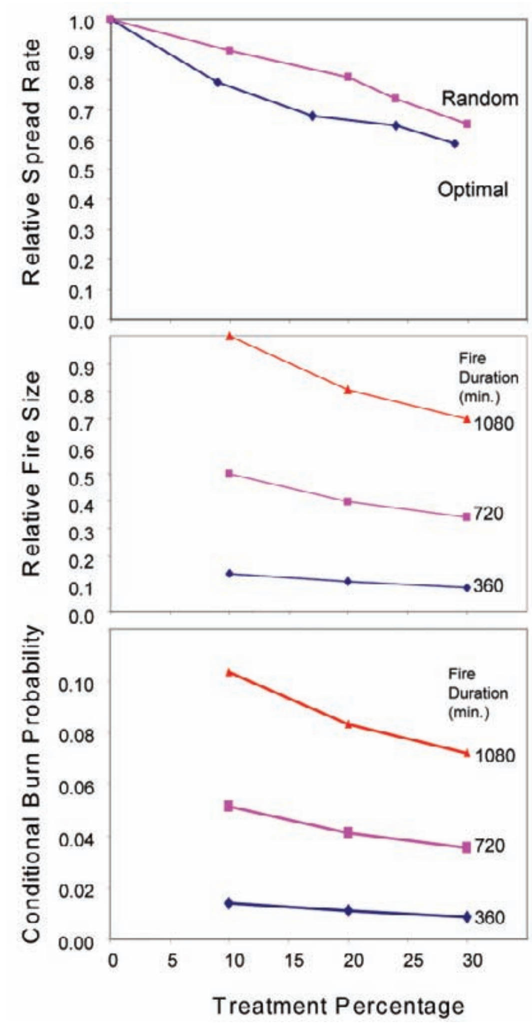

Figure 8—Optimal and random treatment patterns for 1,500 m units on the Flagstaff landscape reduced fire spread rate (a), mean fire sizes (b), and conditional burn probability (c) efficiently compared to random treatments. Although fuel treatments individually reduced fire spread rate by about 90%, the collective benefit of even the optimal pattern was compromised by the presence of large grass meadows that could not be treated. Grass fuels with full wind exposure had spread rates more than four times faster than the forest fuel types and served as conduits for fire growth which reduced effectiveness of treatment pattern in minimizing overall fire growth.

The intent of the optimization was to target treatment locations in areas where fire flow is greatest, meaning that these areas have greater influence on the area burned downwind. The position of the treatment units relative to the slow-burning patches that existed before treatment illustrated how treatment units were positioned to avoid the lee-side wake on the back-side of each of these patches. The major flow paths are located laterally around the left and right flanks of the slow-patches and directed the location of the treatment units.

Maximum treatment unit dimension was varied from 800 to 2,500 m (~0.5 to 1.5 mile diameter, or up to 160 to 960 acres if the units were square) in the optimization but made little difference to the aggregated spread rate, burn probabilities, or the average fire sizes. The flexibility of treatment size would be important to application of treatment units to different landscapes, ecology, topography, and constraints on treatment as illustrated by the Flagstaff example where meadows could not be treated (Figure 7). Treatment unit sizes also affect the optimal spacing between units and appropriateness for wildfires in different fire regimes. Large fire patterns may permit large treatment units and wide spacing, but smaller fires are theoretically little affected by widely spaced treatment units. The possible enhancement of treatment longevity associated with larger units (Finney et al. 2005) may be an additional consideration in selecting treatment sizes for the optimization.

The algorithm developed here was intentionally designed to produce "greedy" solutions for individual treatment units by blocking flow-paths that are identified as "major" only within the current strip. An alternative would be to identify and block fire flow-paths that become important farther downwind than the immediate strip. These two approaches will probably diverge for more complex landscapes because remote downwind landscape conditions (e.g. fuels and topography) may obviate a local pathway. The emphasis on a greedy solution has two advantages. First, it is faster computationally because fire growth does not have to be simulated far downwind from the current strip. Second, and perhaps more importantly for fire management applications, the greedy solution situates a treatment unit on a locally major pathway which increases the proximity of a well-placed treatment unit to a randomly located ignition source.

Amount of treatment tested was limited to 40 percent because theoretical differences between the optimal and random treatment patterns diminish with treatment cover above some level around this point (Finney 2003, 2004). This means that if financial or operational resources permit landscape treatment at a rate sufficient to maintain a landscape at about 30 or 40% treatment annually, then the spatial pattern becomes less important and optimization is not as useful. In natural fire regimes, observed interference by fire history patterns on subsequent wildfire growth (van Wagetndonk 1995, Parsons and van Wagtendonk 1996) is derived from largely random ignition patterns only because the frequency of fire is sufficient to maintain a large fraction of the landscape in a fuel-modified condition.

The spatial optimization assumes that the spatial pattern is extant at a given instant in time. In reality, however, treatments are accomplished on an annual basis and treatment effects to reduced fire behavior diminish with time. To achieve an effective spatial pattern means that the annual rate of treatment or maintenance must be high enough to achieve the cumulative spatial pattern while treatment effectiveness decreases. Little is known about treatment longevity but a few studies suggest that benefits to fire effects are limited to about 10 to 15 years (Biswell et al. 1973, Fernandes et al. 2004, Finney et al. 2005). Consequently, this suggests that the minimum annual treatment rate can be estimated to be about $1/10^{th}$ of the total treatment cover desired. For example, if treatment of 20% of the landscape is a desired state, then the annual rate of treatment must be no lower than approximately 2%.

Spatial constraints are accommodated in the treatment optimization automatically where fire behavior is identical between pre-treatment and potential treatment landscapes. Areas where fuel treatment changes fire spread rate will be considered available for treatment and perhaps selected if intersected by major fire travel paths. Those areas where treatments are not possible contain the same fuel conditions in both landscapes, thereby offering no contrast in fire behavior and no reason for selecting them for treatment even if major flow paths intersect these areas. Such effects can be seen in the large areas with no treatment in the Flagstaff example because of the location of grass meadows and designated wilderness areas that are not available for treatment even though the fire may spread very rapidly (Figure 7).

The current algorithms neglect effects of spotting on fire progression and fuel treatment locations. Spotting is a fire behavior that includes the lofting and transport of burning embers downwind which start new fires and permit fire to breach barriers and discontinuities of fuels. Models for ember production and transport (Albini 1979) are included in other fire behavior systems (Finney 1998) and can be included here in future. The exact effect of spotting on treatment performance is not clear because fuel treatments often limit the source of new embers as well as retard the growth of eventual spot fires. Spotting effects may be minimized by manually increasing the size of treatment units to mitigate overflight possibilities. But longer separation distances between larger treatments permit wider headfires to develop in between treatment units which may increase spot fire generation. Even if spot fires breach the treatment units, an extensive landscape pattern of treatments would impose repeated interruption of any new fires.

Conclusions

The optimization procedure was developed with the intent of obstructing the movement of large wildfires rather than containing them. The algorithm was capable of reducing the average fire growth rate efficiently for complex and simple landscapes. This procedure can be useful for inclusion in fire management planning activities because it offers a means of measuring the performance of fuel treatments at both a stand- and landscape-level.

Acknowledgments

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